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EVALUATION OF DUCTILE PRECAST BEAM-COLUMN CONNECTIONS FOR SEISMIC-RESISTANT BUILDINGS

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ABSTRACT

This paper describes the experimental portion of an investigation of the behavior of ductile connections between precast beam-column elements. Four beam-column subassemblages were tested to characterize the overall behavior of different connection details. Each connection specimen was designed to incorporate one of three behavioral concepts in the connection elements: tension/compression yielding, substantial energy dissipation, and nonlinear-elastic response. A brief description of each specimen is presented, and results of the experimental study are presented using plots of story shear versus interstory drift for all specimens, as well as plots of moment-rotation relationships and strain versus interstory drift for select specimens. Connection elements demonstrating the most promise for future use in precast seismic-resistant frame systems are identified.

KEYWORDS

Beam-column connections; ductile; hysteresis; precast; prestressed; seismic-resistant; subassemblage

INTRODUCTION

Precast concrete construction represents an attractive and economical solution for many types of multistory buildings. Advantages of precast concrete over cast-in-place concrete include superior quality control, speed of erection, and aesthetic architectural form. However, relatively few precast structures are constructed in seismic areas of the United States because framing methods and current connection details between precast elements suitable for use in U.S. construction practice are not explicitly approved in design codes. The current 1994 Uniform Building Code (UBC) classifies precast frame systems, such as those discussed in this paper, as an "undefined structural system". In order to utilize such a structural system, the UBC requires that the lateral-force resistance and energy absorption capacity for this "undefined structural system" be shown by technical and test data to be equivalent to one of the structural systems defined in the code. In effect, current UBC provisions require that precast frames emulate a cast-in-place reinforced-concrete system.

The coordinated research effort "Precast Structural Seismic Systems" (PRESSS) was initiated at a number of locations throughout the U.S. to address this need. The ultimate objectives of the program are to develop precast concrete systems and corresponding design recommendations for seismic regions. The program has sought innovation, taking advantage of the unique characteristics of U.S. precast construction to provide economical building systems. With this philosophy, the research has focused primarily on development of systems which use ductile connection concepts for concrete frame and panel systems. The connections themselves are designed to accommodate most of the lateral deformation, while the precast members remain relatively undamaged. This approach is in sharp contrast to precast construction practice in Japan where buildings are designed using substantially different details and essentially the same design philosophy as is used for cast-in-place concrete buildings (Kurose *et al.*, 1991). Reinforcement details that are substantially different from those used in monolithic construction are used to accommodate connections between the precast members, but the final product has been shown to behave very similar to cast-in-place construction. Because of this, the Japanese precast design approach is often referred to as "emulation design". Earlier research conducted in New Zealand during the 70's (Blakeley and Park, 1971 and 1973) examined the cyclic behavior of precast, prestressed beam-column connections. Blakeley and Park recognized the obvious deformation capabilities inherent in precast, prestressed connections. However, even though these connections were not intended to "emulate" cast-in-place connection behavior, specimen response was evaluated using cast-in-place behavior as the reference. Similar precast, prestressed specimens discussed in this paper were designed and evaluated with quite different behavioral objectives in mind.

This paper describes the PRESSS research conducted at The University of Texas at Austin, which was carried out cooperatively with researchers at the University of Minnesota. The research was divided into three major components: (1) development of ductile connection details, (2) experimental investigation of beam-column subassemblages, and (3) analytical modeling of precast systems. A brief description of the development of connection details is presented here with the measured response of the connections. Because of length limitations, aspects of the analytical modeling of precast frame systems are not presented here. Additional details on all aspects of the research program can be obtained in the reference by Saqan (1995).

A variety of ductile connection details were developed in cooperation with researchers at the University of Minnesota and industry representatives. Connection details were grouped into four behavioral categories: tension/compression yielding, energy dissipating, nonlinear-elastic, and shear yielding. "Tension/compression yielding" refers to energy being dissipated through tension and compression yielding of the connecting elements between beams and columns. "Energy dissipating" refers to the use of a device to produce enhanced energy dissipation in beam-column connections. In this study, a friction device was studied. "Nonlinear-elastic" describes the characteristics of the story shear versus interstory drift response for prestressed beam-column connections. When the story shear attains a level sufficient to open the joint between each precast beam and the column, the response deviates from the original linear-elastic behavior. However, even though behavior is non-linear, the prestressing steel (which remains elastic during design-level events) returns the connection to its undeformed position when story shear is reduced to zero. "Shear yielding" refers to the development of substantial shear deformations in connections between precast elements, much like the shear links used in eccentrically braced steel frames (Popov and Engelhardt, 1988). Connections demonstrating shear yielding were not investigated in this study.

RESULTS OF EXPERIMENTAL INVESTIGATION

To characterize the behavior of the connection details, one-half scale precast beam-column subassemblages were fabricated and tested under reversed cyclic loads. The subassemblages were scaled from a system developed by PRESSS Phase I researchers at Englekirk and Sabol Consulting Engineers, Inc. Lateral-force-resisting elements in this prototype system are concentrated along the perimeter of the frame. Because the connections are intended to resist lateral force reversals along one direction, connection subassemblages were subjected to unidirectional reversed cyclic loads.

The one-half scale test specimens represented interior beam-column joints located in the lower stories of the peripheral frames spanning in the short direction of the 15-story prototype structure. The required nominal moment capacities for the connections tested in this study were scaled from the prototype structure. The design moment M_u, for the prototype structure was 2283 ft-k; the calculated one-half scale design moment was 285 ft-k. A strength reduction factor of 0.9 was used to obtain the nominal moment capacity, M_n, of

317 ft-k. The interstory drift level (ratio of story lateral displacement and story height) under the nominal moment M_n was targeted to be 2 percent.

The subassemblages were subjected to increasing drift levels comprising the following sequence: one cycle each at 0.05, 0.075, and 0.1% drifts, followed by three cycles each at 0.25, 0.5, 0.75, 1, 1.5, 2, 2.5 and 3% drift. After each set of three cycles, an intermediate cycle was imposed to a peak load of 75 percent of the previously attained peak load to investigate stiffness degradation. One specimen was subjected to two cycles at 4% and 5% drift.

Limited details and schematic drawings of the four test specimens, and results of reversed cyclic load tests conducted on those specimens are presented in the following subsections.

Tension-Compression Yielding Concept

Two of the subassemblages tested, Specimens DB-TC and GJ-TC, represented examples of the tension-compression yielding concept. Specimen GJ-TC was representative of the "gap-joint system" which received very favorable reviews from the precast industry advisory group (See schematic of connection in Fig. 1). In the gap-joint system, the beam is intended to be restrained from translation at the bottom (or top) of the beam-column interface, while lateral movement is accommodated by rotation about that point through opening and closing of a "gap" (1 in. wide in this specimen) at the top (or bottom) of the interface. The gap system is desirable for two reasons. (1) It enables ease of fabrication of the bottom connection; the erectors can lower the beam into place and complete both the top and bottom connection while working from the top of the beam. (2) If the gap is provided at the bottom of the beam, the lack of translation at the top surface will prevent large cracks from developing across the floor panels at the beam-column interface under cyclic lateral loading. For gap-joint connections like Specimen GJ-TC, the gap at the interface of the beam and column facilitated both tension and compression yielding of the connecting elements.

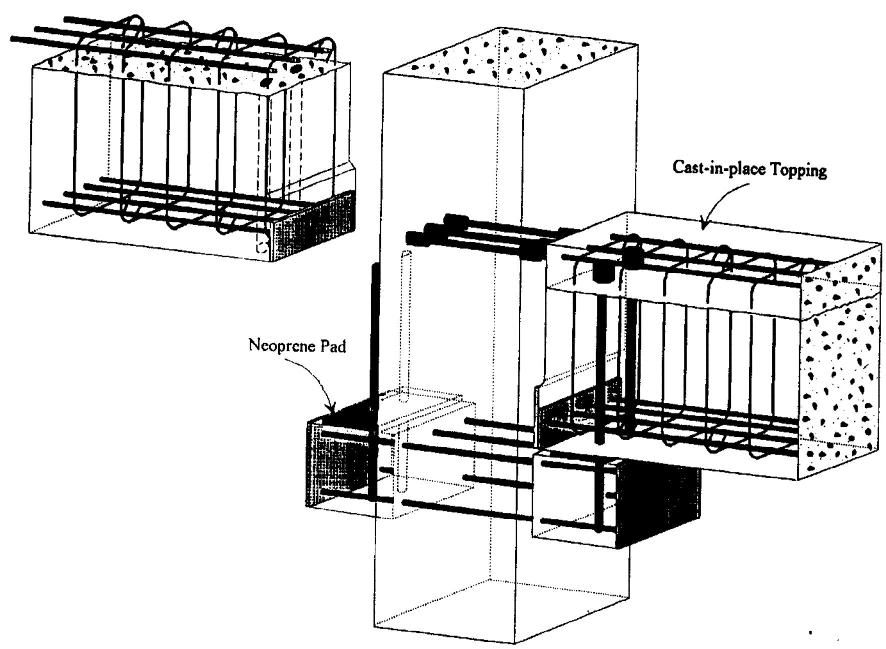

Fig. 1 Schematic of Specimen GJ-TC

Specimen GJ-TC incorporated tapered threaded couplers in the column to mate with mild reinforcement (with a nominal yield stress of 60 ksi) in the top of the beam. The bottom horizontal connection and resistance to beam-end uplift were provided by four high-strength vertical rods anchored in the corbel. Oversized holes in the beam provided sufficient construction tolerance to slip the beam ends over the rods. Following placement of the beams, nuts were fastened to the ends of the rods, then the voids around the rods were grouted. Each beam was seated on a neoprene pad to accommodate the rotation of the beam without causing damage to the corbel. Fiber-reinforced grout was placed in the bottom of the gap between the beams and column to facilitate direct transfer of compression forces from the bottom of each beam to the column. The tops of the beams were cast after the beam top bars were screwed into threaded couplers embedded in the columns.

Response of the specimen is illustrated in Fig. 2 using story shear versus interstory drift ratio (hereafter referred to as drift). Overall response of the connection was reasonably good through cycles to 2.5% drift. However, some pinching of the hysteresis loops was evident with the onset of inelastic behavior at approximately 0.6% drift. Most of the pinching was attributed to shear and flexural deformations that occurred in the vertical rods at the interface between the corbels and beams. This slip between the two members is indirectly demonstrated in Fig. 3 by the moment-rotation response of one of the beams. Note that stiffness was generally less for loading in the positive-moment direction (which corresponded with opening of the gap at the bottom of the beam). Deformation of the vertical rods at the beam/corbel interface became more pronounced at higher deformation levels and eventually dominated the response. Failure of Specimen GJ-TC occurred as the result of fracture of the vertical rods during cycles to 3% drift (note strength reductions in Fig. 2). The compliant bottom connection also affected the inelastic response of the beam top bars which were intended to experience most of the inelastic action in the connection. Figure 4 illustrates the stress-strain response of a beam top bar at the face of one of the beams. Note that tensile inelastic strains (corresponding with opening of the gap at the top of the beam) are substantially greater than compressive inelastic strains.

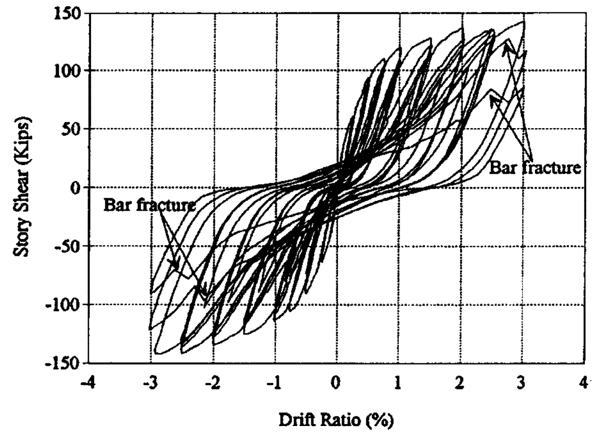

Fig. 2 Story Shear vs Drift Ratio, Specimen GJ-TC

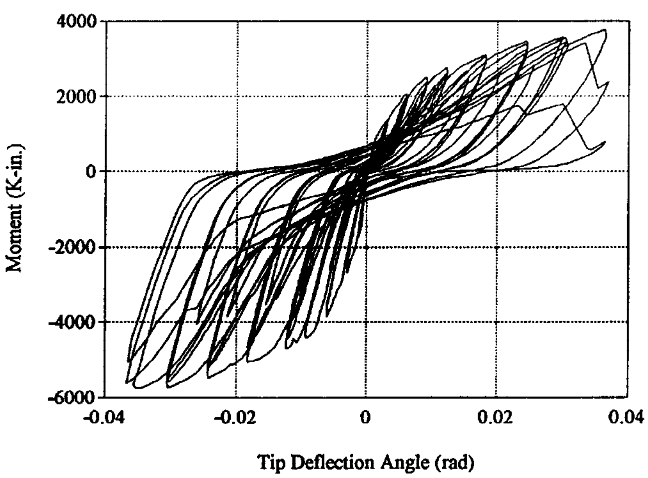

Fig. 3 Beam Moment vs Beam Deflection, Specimen GJ-TC

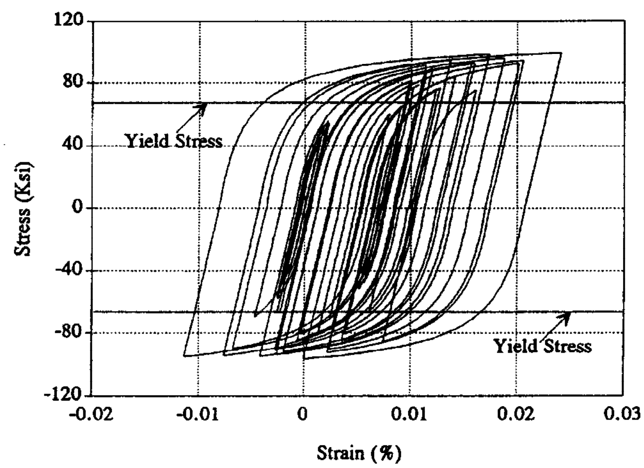

Fig. 4 Stress-Strain History of Beam Top Bar, Specimen GJ-TC

Specimen DB-TC employed vertical "dogbones" and high-strength threadbars to connect precast beams and columns (See Fig. 5). High-strength fiber reinforced grout was placed between the beam ends and the column before the beams were connected to the column. Ducts that contained the threadbars were grouted after the threadbars were snug tightened. The story shear versus drift response is illustrated in Fig. 6. Connection behavior was reasonably acceptable through 1% drift cycles, although the high-strength threadbars resulted in less energy dissipation than would be anticipated for monolithic beam-column connections. During loading in the positive direction to 1.5% drift, concrete located between the 90 degree hooks on the longitudinal beam reinforcement and the anchor plates at the ends of the dogbones crushed. The same behavior was observed at approximately 2% drift when the connection was loaded in the negative direction.

Use of connecting elements that provided an indirect path for force transfer between precast elements was the common thread that precipitated the premature failure of Specimens GJ-TC and DB-TC.

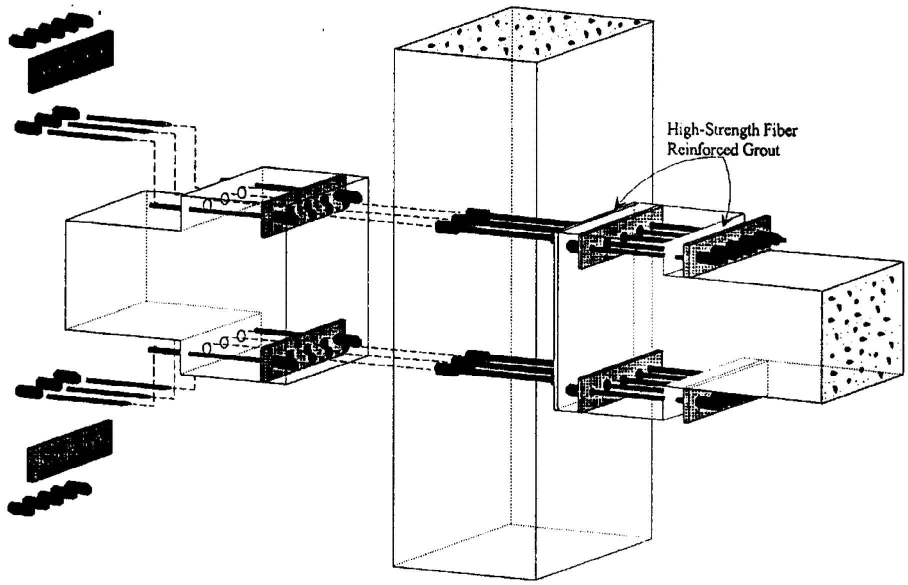

Fig. 5 Schematic of Specimen DB-TC

Energy Dissipating Concept

Specimen GJ-FR was the only connection tested in this program that incorporated special connection hardware to enhance the energy dissipation capacity of the beam-column subassemblage. The connection details are illustrated in a schematic shown in Fig. 7. The top of each beam was connected to the column by a steel plate assembly that was embedded in the beam and bolted onto the side of the column. The plate assemblies contained 4 in. slotted holes that permitted sliding along vertical plate surfaces on the sides of the beams. Consistency in the level of force required to cause sliding along these plate surfaces was obtained by placing 1/8 in. thick brass plates between all sliding surfaces. The friction coefficient for brass sliding on steel was approximately 0.2. The force required to cause slip on these plate surfaces was controlled by the clamping force applied to the plates, which was maintained relatively constant by placing conical (belleville) washers beneath the high-strength bolts that clamped the plates together. The concept for this friction connection stemmed from work conducted by Gregorian, Yang and Popov (1992).

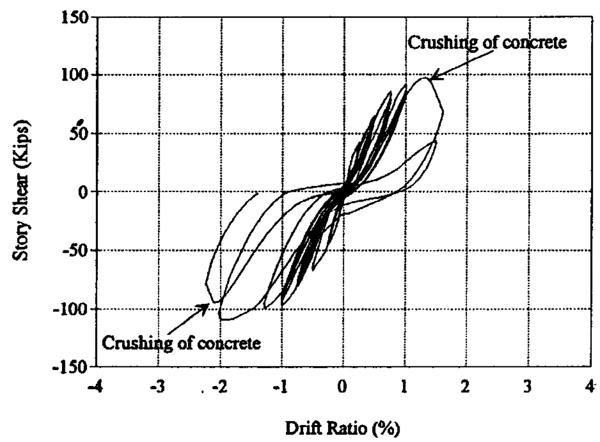

Fig. 6 Story Shear vs Drift Ratio, Specimen DB-TC

The bottom connection between the beams and column was developed to replace the corbel which performed relatively poorly in Specimen GJ-TC. Note that the bottom connection shown in Fig. 7 provided a direct path for force transfer from the bottom of the beams into the column, as well as a much more aesthetically pleasing detail. Three 1-1/8 in. diameter A490 bolts were used to connect the bottom of each beam with the corbel. The line of bolts was also intended to act as a pivot point for beam rotation.

Specimen GJ-FR behaved quite well through the first two cycles to 3% drift (See story shear versus drift response in Fig. 8). Energy dissipation was enhanced, as intended, and was substantially greater than for any of the other specimens tested in this study. Testing was terminated during the third cycle to 3% drift because a weld between plates in one of the top connections failed as a result of larger-than-anticipated forces being developed in the connections. It was anticipated that the hysteresis loops shown in Fig. 8 would

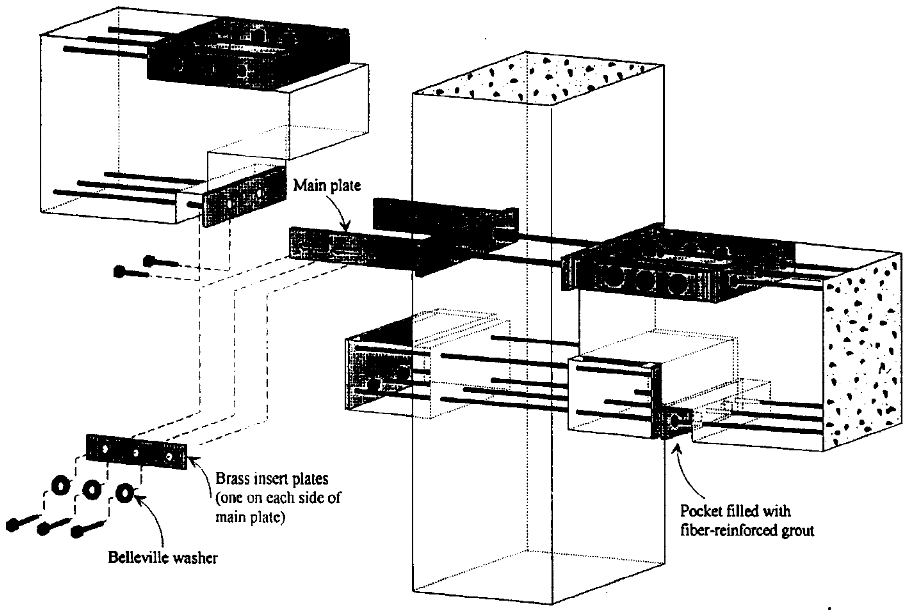

Fig. 7 Schematic of Specimen GJ-FR

resemble elasto-plastic behavior. However, rotation of the beams forced some bolts in the friction devices to bear against the sides of the slotted holes, and resulted in the post-slip stiffness that is evident in the story shear versus drift plot. As a result, demand on many of the components used in the connection (such as the failed weld between plates) exceeded design capacities. The assemblage of plates used in the top connections and the high-strength bolts used in the bottom connections introduced connection flexibility at low drift levels that was approximately twice that observed for the other specimens. Designers should be aware that the overall flexibility of precast beam-column connections is very sensitive to the stiffness of the connecting elements, and as result, proportions of connections between precast elements can be controlled by stiffness rather than strength.

Nonlinear Elastic Concept

Specimen PT-NE was intended to investigate nonlinear-elastic behavior. The subassemblage consisted of a pretensioned, precast beam that was continuous through the connection region, and two precast column elements, one each above and below the beam (Fig. 9). The prototype system from which this specimen was derived was envisaged to have precast beam elements that spanned from midspan to midspan over two columns. Beams would be connected at midspan to resist shear and gravity moments only. Precast column elements would span between floors. Specimen PT-NE was pretensioned using 20 centrally-located 3/8 in. diameter strands pretensioned to $0.4f_{pu}$ (nominally 108 ksi). In order for the strands to remain elastic through specimen drifts of 2%, they were debonded through the joint and for 2 ft on each side of the column (a total of 69 in.). Spiral reinforcement was placed in the top and bottom of each beam in the 18 in. adjacent to the column to confine the concrete and permit large rotations at the beam-column interface. Approximately 75% of the joint reinforcement recommended by ACI-ASCE 352 (1985) was used in the specimen. This was done with the hope of precipitating a joint failure because none of the other specimens exhibited signs of significant distress in the joint region, and because the force transfer mechanism for joints in prestressed specimens (with unbonded prestressing through the connection) is comprised primarily of a direct compression strut (a mechanism which differs substantially from behavior of monolithic joints at low load levels).

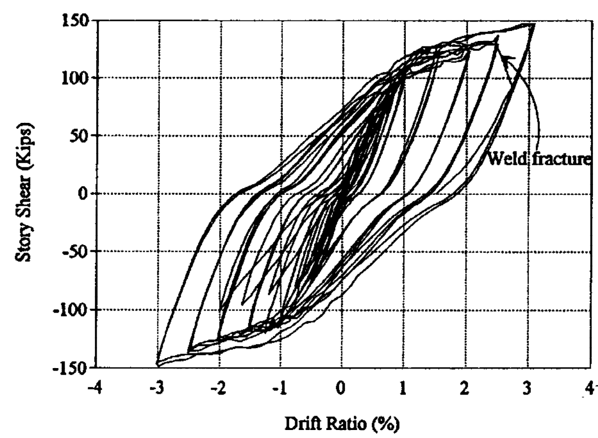

Fig. 8 Story Shear vs Drift Ratio, Specimen GJ-FR

Specimen PT-NE was assembled by lowering the beam/joint segment over the 16 column bars that protruded from the top of the lower column segment. The half inch gap that was left between the lower column segment and the beam/joint segment was grouted along with the ducts in the beam/joint segment. The upper column segment was lowered into position and column bars were joined immediately above the beam using threaded couplers. The recess provided around the base of the upper column segment to accommodate the threaded couplers was filled with fiber-reinforced grout.

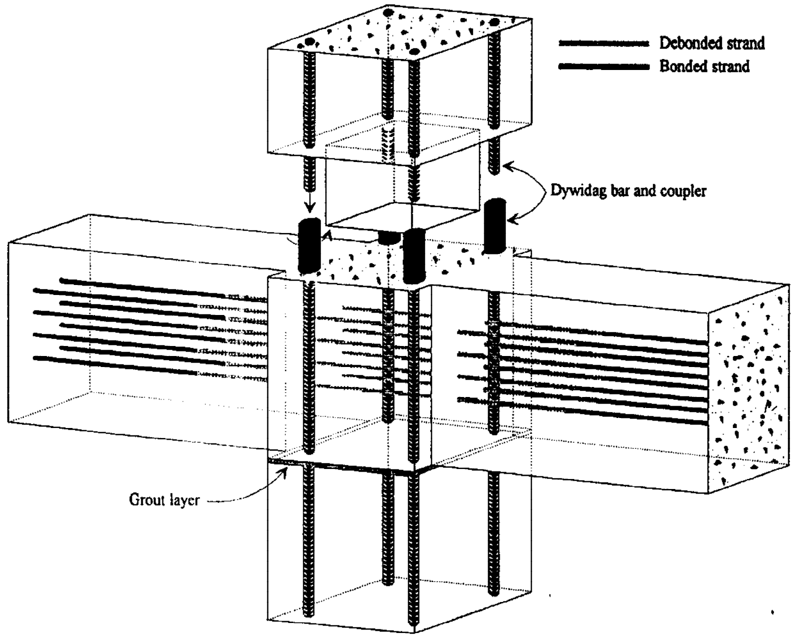

Fig. 9 Schematic of Specimen PT-NE

Story shear versus drift response for the specimen is shown in Fig. 10. Behavior through 2% drift cycles loosely resembled nonlinear-elastic behavior and exhibited pinching of the hysteresis loops at low drift levels. Pinching was the result of slip in the column bar couplers once the column cracked. The pinching would have been substantially less if axial load had been applied to the column (no axial load was applied to any of the columns) and if commercial products intended for coupling conventional bars had been used. Commercial bar couplers were not used because of the extreme congestion that existed in the half-scale specimen.

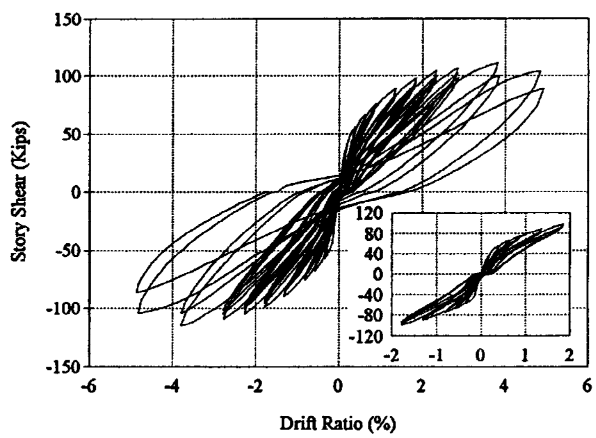

Fig. 10 Story Shear vs Drift Ratio, Specimen PT-NE

Energy dissipation increased markedly during the cycles to 4% drift, but not as the result of yielding of strands. Strain gages mounted on strands in the debonded regions indicated that strands remained elastic throughout the test. It is presumed that bond between the concrete and strand deteriorated outside the debonded region (increasing the debonded length) as the test progressed. The substantial increase in energy dissipation is attributed to failure of the joint. Although transverse reinforcement began yielding at approximately 1.5% drift, significant dilation of the joint and obvious crushing of concrete along diagonals of the joint were not evident until cycles to 4% drift were administered.

SUMMARY

All but Specimen DB-TC performed well through design-level drifts. This subassemblage experienced concrete crushing in the dogbone regions of the beams as a result of using a connection detail that incorporated an indirect path for transfer of forces at the ends of the beams. This same problem (indirect force path in the connection region) contributed to failure of Specimens GJ-TC (fracture of dowel bars in the bottom connection between beams and corbel) and PT-NE (fracture of a weld in the energy-dissipating connection) during 3% drift cycles. The indirect force path inherent in the connections also resulted in additional flexibility that was most apparent at low drift levels. Particular attention must be paid to designing connection elements for appropriate levels of stiffness.

Although not all specimens performed as well as others, most contained at least one connection detail that demonstrated good performance throughout testing. For example, the corbel/dapped beam combination used in Specimen GJ-FR did not deteriorate during testing and provided a well-defined "pivot point" to accommodate deformations in connections used in the top of beams. Note that this connection could also be used as a top connection between beams and a column in order to avoid distortion and damage in the slab/horizontal diaphragm. Care must be exercised, however, in choosing the other connection to be paired with this connection because the rigidity of the corbel/dapped beam connection will place large inelastic demands on the complementary connection.

Pretensioned Specimen PT-NE exhibited the desired nonlinear elastic behavior through 3% drift levels, and also experienced minimal residual drifts during cycles through the design drift level. Energy dissipation for this connection was quite low for the design drift level. In contrast, energy dissipation for the connection containing a friction device (Specimen GJ-FR) was quite high. The higher cost associated with the friction connection may preclude the use of such a connection throughout a structure, but the superior energy dissipating characteristics suggest that a few of these connections placed at strategic locations in a structure, such as one utilizing prestressed connections, may dramatically improve the overall seismic resistance of the structure.

All but one of the subassemblages tested contained transverse reinforcement in the joint that was quite similar to that recommended by ACI-ASCE 352 (1985). None of these connections demonstrated signs of joint distress, indicating that the ACI-ASCE 352 provisions are conservative for the design of most precast beam-column joints. Specimen PT-NE was constructed with 75% of the joint reinforcement recommended by Committee 352. The specimen maintained strength and showed no signs of distress until the second drift cycle to 4%. More attention should be directed in the future to development of a design procedure for joint reinforcement in prestressed connections.

ACKNOWLEDGEMENTS

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